Integrated Fire Engineering and Response
COST ACTION TU0904

# STUDY OF THE BEHAVIOUR OF STEEL AND COMPOSITE STRUCTURES IN FIRE-AFTER-EARTHQUAKE EVENTS

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## Outline of PhD thesis

- ✓ The objective of the PhD thesis is the study of the behaviour of steel and composite structures in the combined scenario of fire after a seismic event using numerical methods.
- ✓ This situation is not covered till now by the structural design codes.
- ✓ Of primary interest is the effect of damage of both structural and non-structural elements due to earthquake, to the evolution of fire in real structures.
- ✓ The structural behaviour in fire is studied starting from the stress and strain state which was induced in the structure by a design earthquake.
- ✓ The results of the project will allow the development of certain design procedures to cover the considered situation.

# State of the art

- ✓ The case of fire resulting just after an earthquake event has been witnessed by the international community after the major earthquakes in recent years (Kobe-Japan earthquake 1995, Northridge earthquake 1994, etc.)

- ✓ According to the current design codes the design of structures is performed independently for the seismic and thermal actions.

- ✓ Despite the progress in the research on earthquake response and fire, the research on the combined effect of seismic and thermal actions on structures has only very recently been started.

## State of the art

- ✓ Fire design codes make the assumption that

  - at the beginning of the fire event, the structure is still in the elastic region of material behaviour,
  - all the measures for fireproofing are active (fire coatings, paints, sprinkler systems, etc. ).

- ✓ However, this assumption is not valid when the structures are damaged by seismic events, which are followed by the outbreak of fire.

## Innovation of PhD thesis

In this study the fire behaviour is studied, considering that the structure is damaged by earthquake

Earthquakes may cause damage to → structural / → non-structural elements

# Innovation of PhD thesis

- ✓ For the structural components the damage can be either brittle or ductile, which means that when the fire event occurs, the structure will be in a completely different state from that which has been considered in the design against fire
- ✓ The damage to non-structural elements due to earthquake, may limit the resistance of structures in fire (e.g. cracking of fireproof cladding, peeling of fireproof painting due to intense plastic deformation, sprinkler failure etc)
- ✓ Moreover, seismic damages significantly affect the conditions of growth and spread of fire (e.g. breakage of windows allowing free air inflow, blocking of fireproof doors, etc)

# Organization of the PhD Thesis

**W.P.1** Study of the literature

**W.P.2** Detailed numerical simulation of the behaviour of structural members at elevated temperatures

**W.P.3** Non-linear analysis of structures for seismic loading, under the performance-based design philosophy

**W.P.4** Simulation of the natural fire event using CFD

**W.P.5** Numerical simulation of the structural behaviour of framed structures at elevated temperatures

**W.P.6** Analysis of framed structures under the combined scenario of fire after earthquake

**W.P.7** Conclusions - Development of design procedures for covering the combined scenario

## W.P.2 Detailed numerical simulation of the behaviour of structural members at elevated temperatures

- ✓The target of this W.P. is the development of advanced three-dimensional models that can be used for the simulation of the behaviour of structural steel members at elevated temperatures

- ✓The three – dimensional numerical models are developed using the non-linear finite element code MSC Marc

- ✓The problem is handled through coupled thermo-mechanical analysis in the context of the finite element method

- ✓First of all, the objective is to ensure that the developed numerical models can describe adequately the complex behaviour of structural steel at elevated temperatures

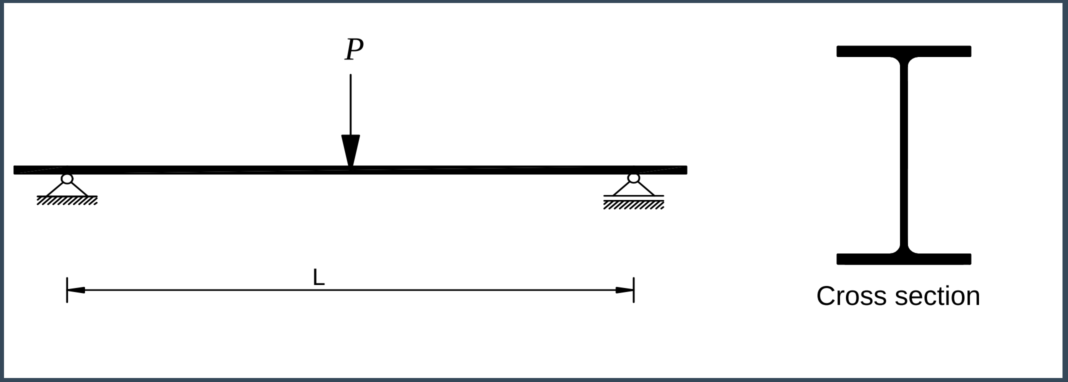
- ✓For this purpose, experimental or numerical studies, available in the literature are used for comparison

# W.P.2 Detailed numerical simulation of the behaviour of structural members at elevated temperatures

## 1. Numerical simulation of the behaviour of steel beam -column structural elements at elevated temperatures

**The aim is to obtain moment – rotation functions, in the possible plastic-hinge locations, that take into account all the factors that affect the ductility of steel beams-columns at elevated temperatures**

**In order to simplify the problem the rotational capacity is evaluated through a simply supported steel I-beam under fire conditions**




**These functions can be used for the global plastic analysis of frame structures under fire conditions through more simple commercial software packages, utilizing beam finite elements**

# W.P.2 Detailed numerical simulation of the behaviour of structural members at elevated temperatures

## 1. Numerical simulation of the behaviour of steel structural I-beams at elevated temperatures

The three-dimensional numerical models are based on shell finite elements and take into account the initial imperfections of the steel members.

Moment-rotation curves are obtained taking into account the different temperatures, under the consideration that temperature of the beam is uniform and constant.

✓Validation of the numerical model against the published experimental results (experimental study by R.B. Dharma and K.H. Tan. )

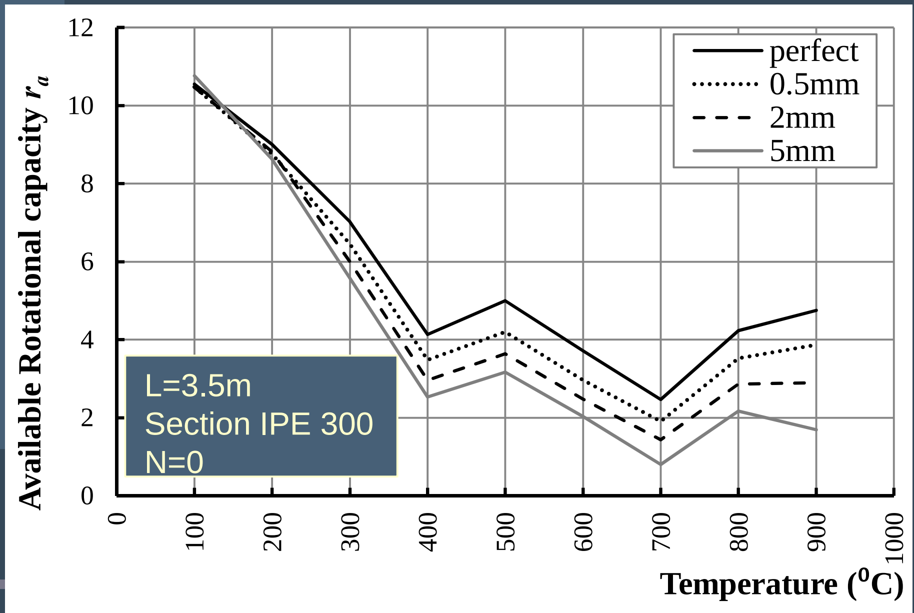
✓ Parametric analyses are conducted with respect to

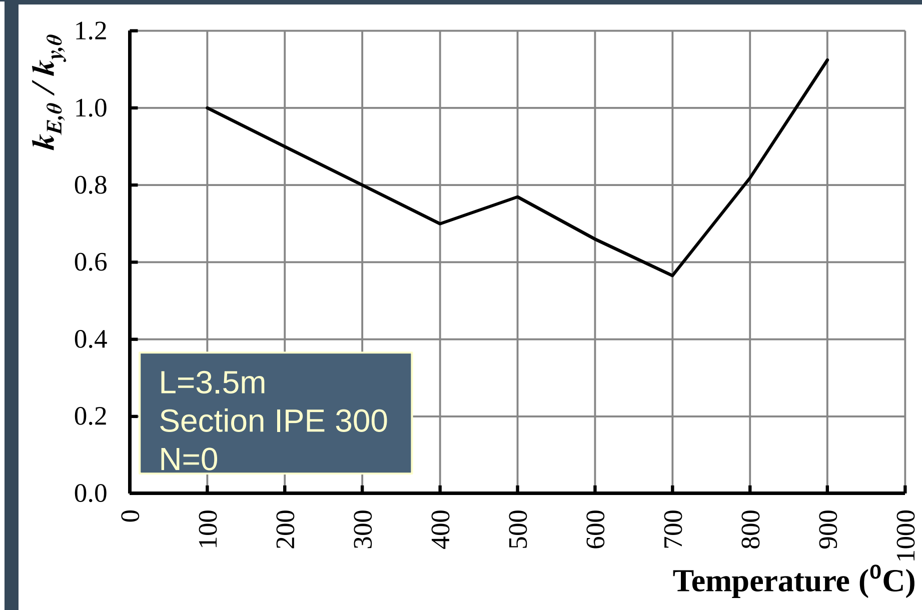
- the temperature level
- the slenderness of both the flange and the web
- the amplitude of the initial imperfections,
- the length of the beams
- the level of axial forces (tensile or compressive)

# W.P.2 Detailed numerical simulation of the behaviour of structural members at elevated temperatures

## 1. Numerical simulation of the behaviour of steel structural I-beams at elevated temperatures

Available rotational capacity of an IPE 300 steel beam at various temperature levels




It is noticed that

- ✓ both the initial imperfections and temperature have a significant effect on the available rotational capacity
- ✓ the rotational capacity seems to be increased for temperatures above 700$^0$C with respect to the values obtained for lower temperatures

## W.P.2 Detailed numerical simulation of the behaviour of structural members at elevated temperatures

### 2. Thermo-mechanical modeling of composite slabs with thin-walled steel sheeting submitted to fire

✓A detailed numerical model is developed to assist the evaluation of the behavior of composite slabs in elevated temperatures.

The finite element model uses:

- ➢3d solid elements for concrete
- ➢4-node shell elements for steel profile
- ➢3d frame elements for reinforcing steel bars

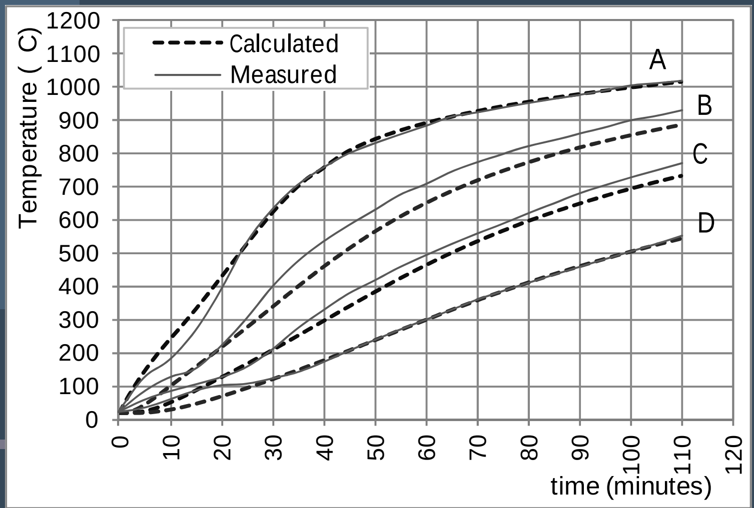
✓The thermal loading is applied on the lower side of the slab and follows the standard ISO 834 fire curve

✓Coupled thermo-mechanical analysis is performed

# W.P.2 Detailed numerical simulation of the behaviour of structural members at elevated temperatures

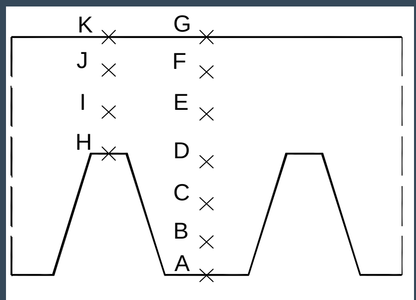
## 2. Thermo-mechanical modeling of composite slabs with thin-walled steel sheeting submitted to fire

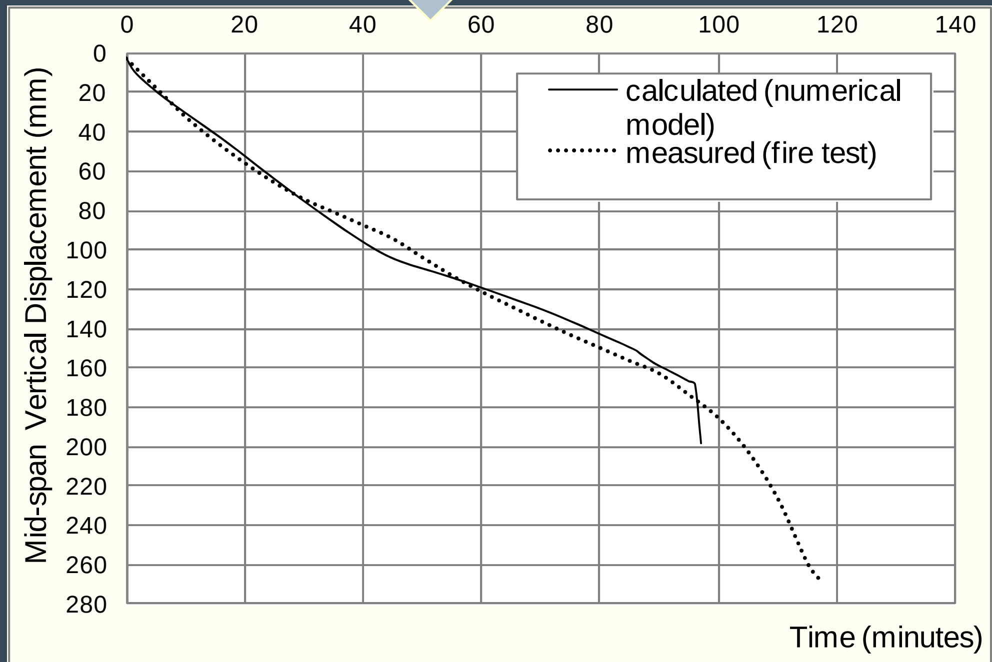
✓**Validation of the numerical model against the published experimental results considering both the mechanical and the thermal results (experimental study by Hamerlinck )**




Results of heat transfer analysis

Results of mechanical analysis



## W.P.2 Detailed numerical simulation of the behaviour of structural members at elevated temperatures

### 2. Thermo-mechanical modeling of composite slabs with thin-walled steel sheeting submitted to fire

✓The basic objective is to assess the thermal behavior of composite slabs through both simple and advanced calculation models and compare their results.

**Simple calculation models** ↓ expected fire resistance according to Eurocode 4

⟷ comparison

**Advanced calculation models** ↓ results of the thermo-mechanical analysis

✓Another objective is to study the fire performance of the steel-concrete slabs considering two structural systems:

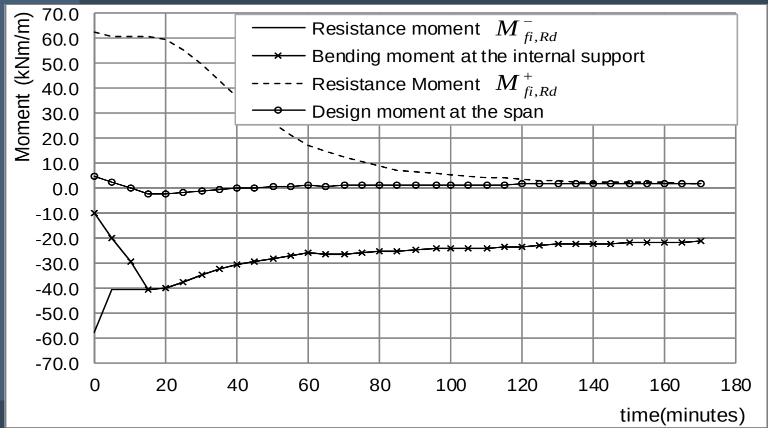
**simply supported slab** ⟷ **comparison** ⟷ **two span continuous slab**

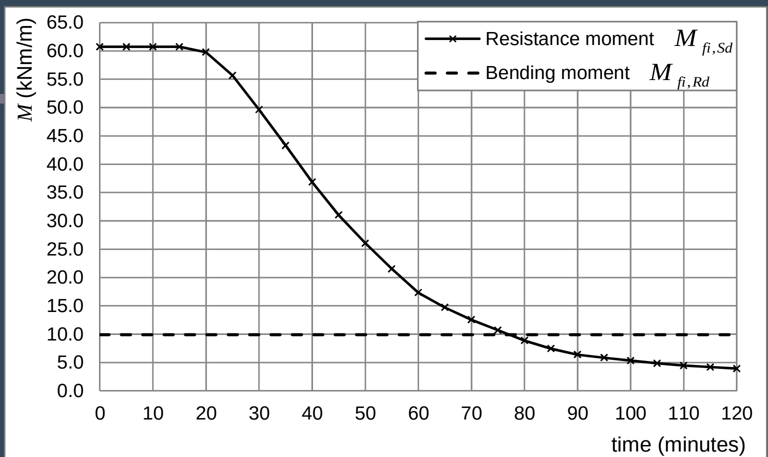
The goal here is to evaluate the effect of static indeterminacy on the fire resistance of composite slabs.

# W.P.2 Detailed numerical simulation of the behaviour of structural members at elevated temperatures

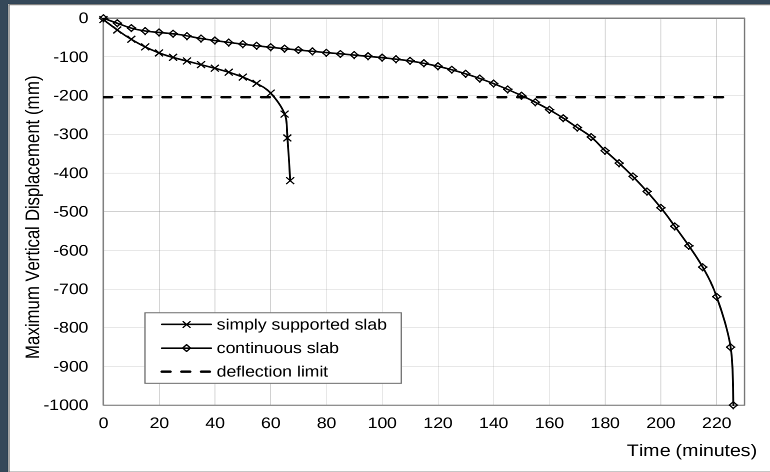
## 2. Thermo-mechanical modeling of composite slabs with thin-walled steel sheeting submitted to fire

### Simple calculation models




### Advanced calculation models



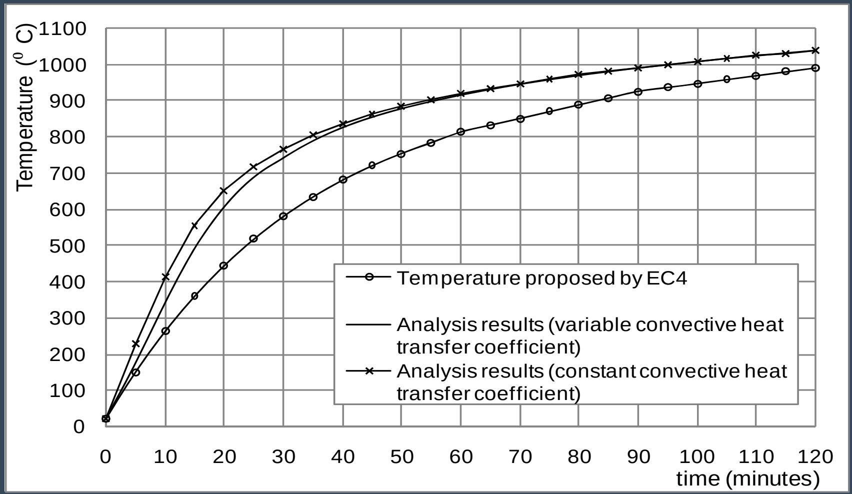

### Comparison

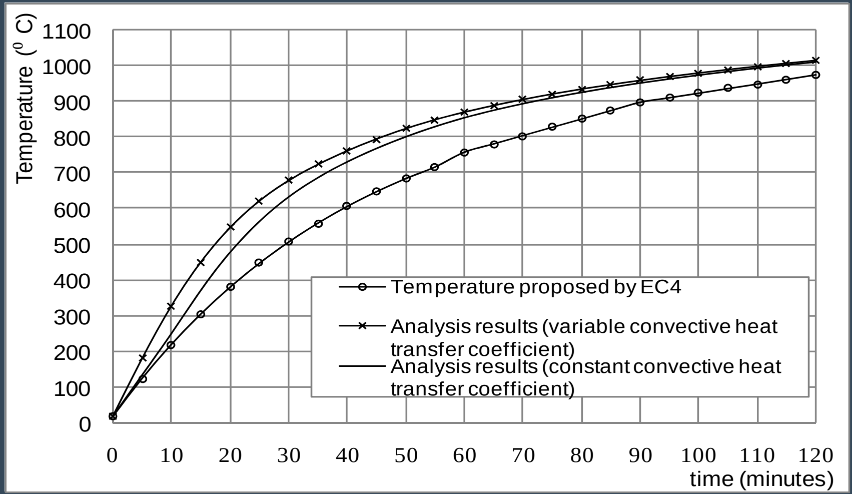
| | Simply supported slab | Continuous slab |
|---|---|---|
| Simplified model | 77 mins | 170 mins |
| Advanced calculation model | 67 mins | 226 mins |
| Deflection limit criterion | 62 mins | 152 mins |
| Rate of deflection criterion | 62 mins | 203 mins |

# W.P.2 Detailed numerical simulation of the behaviour of structural members at elevated temperatures

## 2. Thermo-mechanical modeling of composite slabs with thin-walled steel sheeting submitted to fire

✓the results of the thermal analysis which is conducted according to the principles of the heat transfer theory, applied through the finite element method, are compared with the temperature profiles for composite slabs proposed by Eurocode 4



# W.P.3 Non-linear analysis of structures for seismic loading, under the performance-based design philosophy

✓The **main objective** of this W.P. is to design the model structures against earthquake taking into account different performance levels

✓The required performance of buildings against earthquake events is defined from the structural performance, the non-structural performance and the earthquake intensity

| Characterization | Probability of existence | Return Period |
|---|---|---|
| Frequent | 50% in 50years | 72years |
| Moderate | 20% in 50years | 225years |
| Rare | 10% in 50years | 475years |
| Vary Rare | 2% in 50years | 2475years |

| | | Target performance levels | | | |
|---|---|---|---|---|---|
| | | Operational | Immediate | Life Safety | Collapse prevention |
| Earthquake hazard level | Frequent | A | B | C | D |
| | Moderate | E | F | G | H |
| | Rare | I | J | K | L |
| | Vary Rare | M | N | O | P |

## W.P.3 Non-linear analysis of structures for seismic loading, under the performance-based design philosophy

✓Another factor that is taken into account is the design ground acceleration and the type of the ground

✓The design is based on the guidelines of Eurocode 8 using different design spectrums and taking into account the requirements for the different performance levels

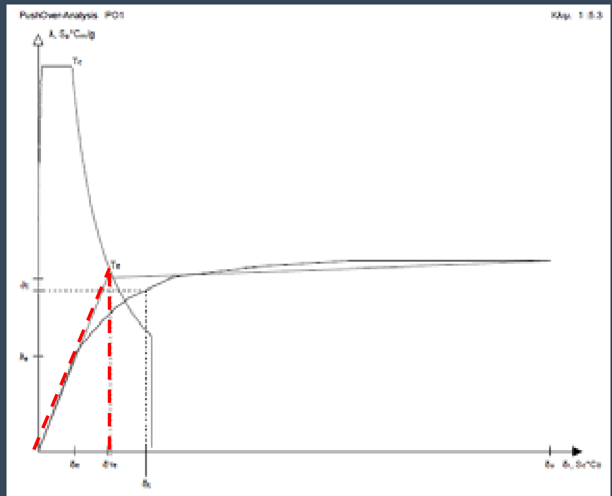
✓Primarily, the structural performance of the model structures, against earthquake, is obtained through non-lineal pushover analysis (Cubus software-Statik)

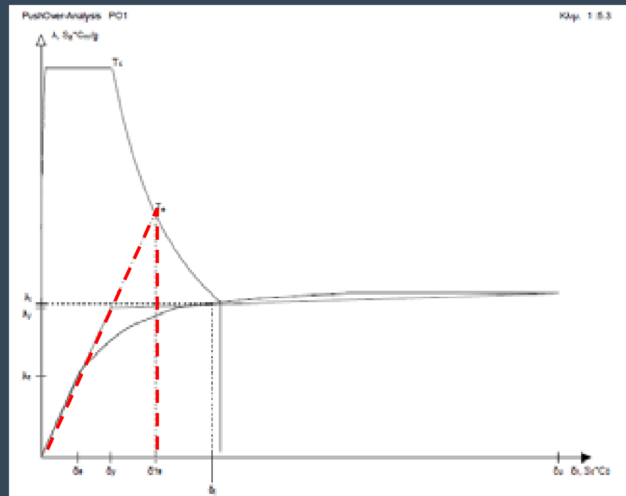
✓The target displacement for the different performance levels is obtained according to Eurocode 8

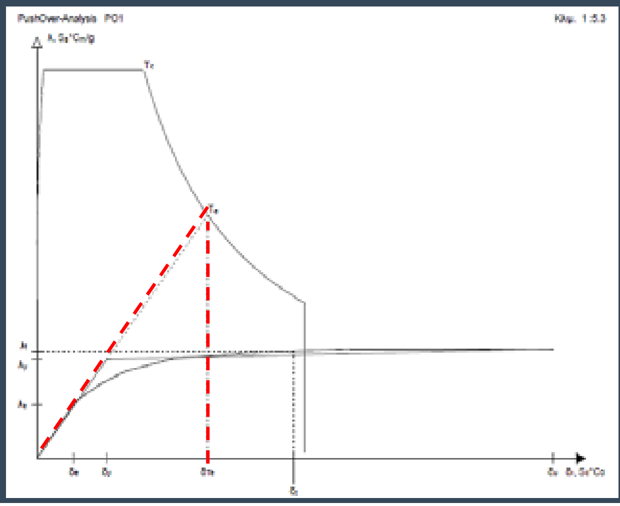
# W.P.3 Non-linear analysis of structures for seismic loading, under the performance-based design philosophy

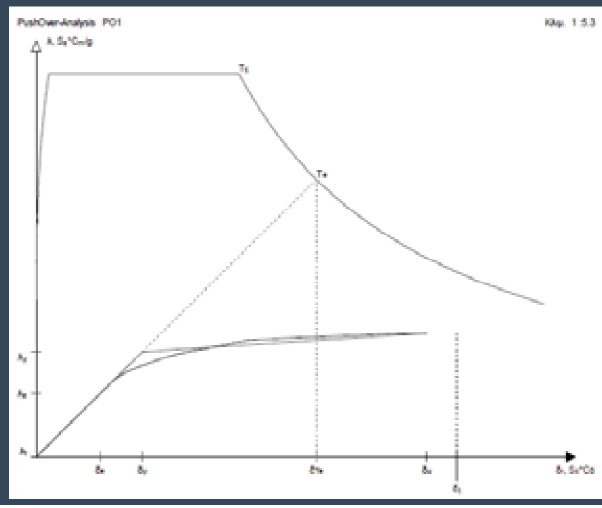
## 1. Non-linear analysis of a 4th storey steel frame building for seismic loading

### Pushover curves for different earthquake spectrums









# W.P.4 Simulation of the natural fire event using CFD

✓The basic goal of this W.P. is the simulation of the natural fire event through Computational Fluid Dynamics in order to obtain the temperature-history for the structural members

✓The simulation is conducted through FDS. Fluid Dynamics Simulator is a computational fluid dynamics (CFD) model of fire-driven fluid flow

✓The software solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires

✓The equations describing the transport of mass, momentum and energy by the fire-induced flows are solved in a simplified form (Rehm and Baum equations).

✓The so-called low Mach equations are solved numerically by dividing the physical space, where the fire occurs, into a large number of rectangular cells

✓The physical phenomenon of combustion is model through the mixture fraction concept

# W.P.4 Simulation of the natural fire event using CFD

✓The target is to obtain different fire scenarios, taking into account damages to non-structural members due to earthquake

## 1. Numerical simulation of the natural fire event in an industrial building using FDS

**Fire scenario**

**Reference State:** All the windows are closed – sprinklers are working properly

**Fire-after –earthquake scenarios**

**Scenario1:** 25% of the windows are broken – sprinklers are working properly

**Scenario2:** 50% of the windows are broken – sprinklers are working properly

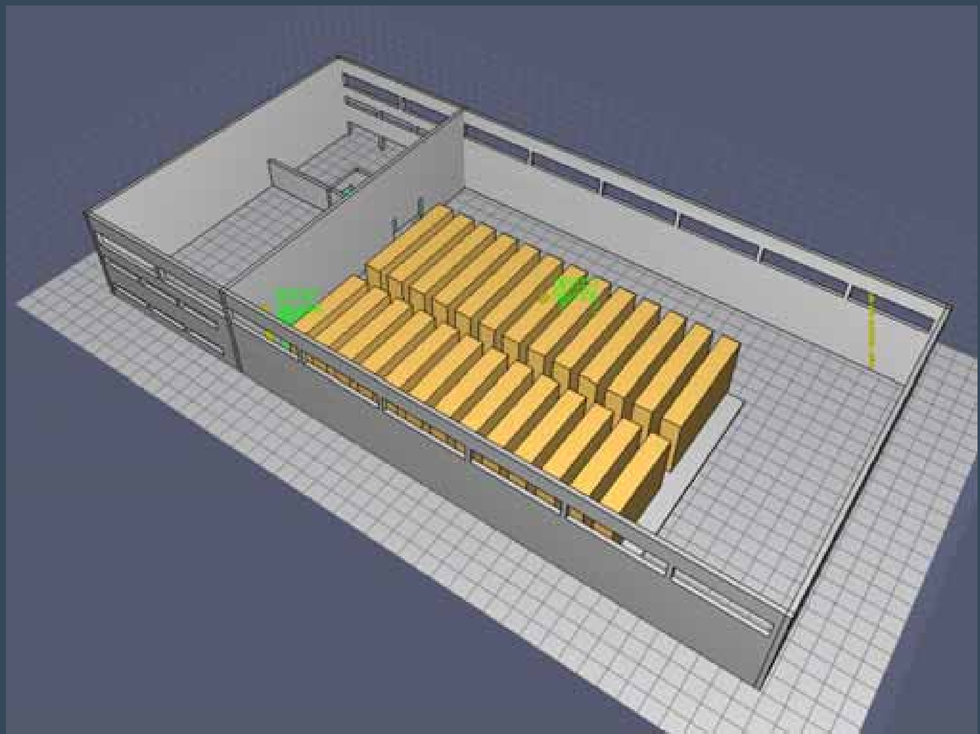
**Scenario3:** 100% of the windows are broken – sprinklers are working properly

**Scenario4:** 25% of the windows are broken – sprinklers failure

**Scenario5:** 50% of the windows are broken – sprinklers are broken- the fireproof doors are blocked

## W.P.4 Simulation of the natural fire event using CFD

### 1. Numerical simulation of the natural fire event in an industrial building using FDS



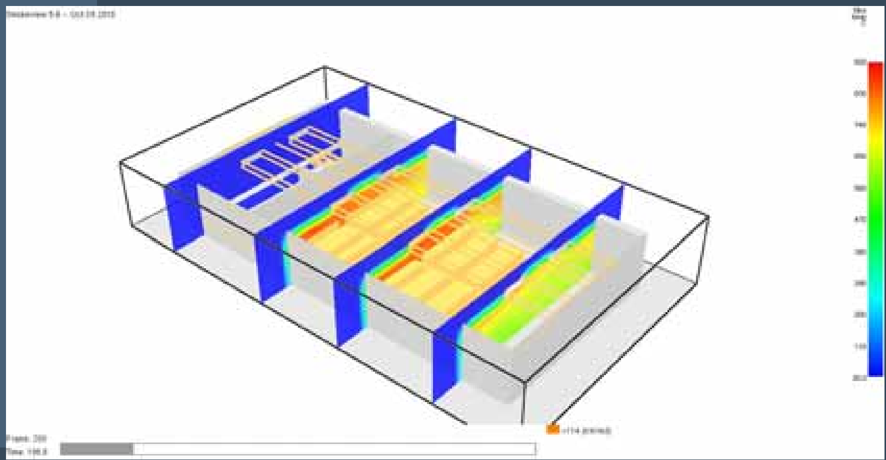
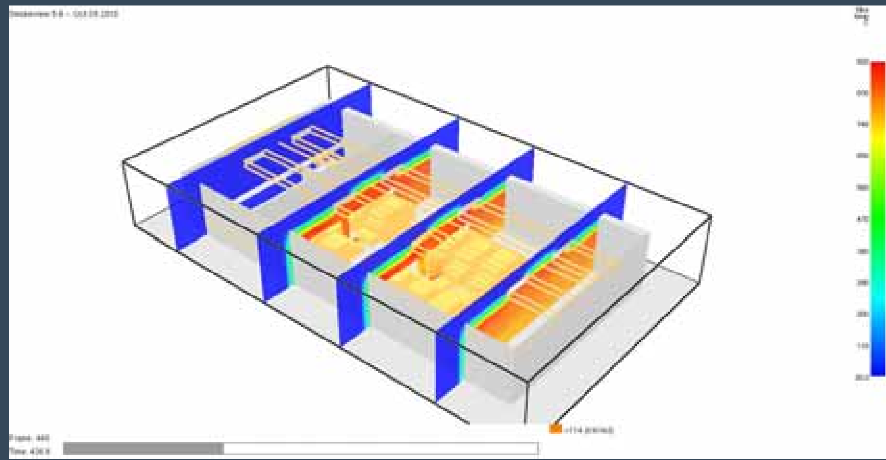
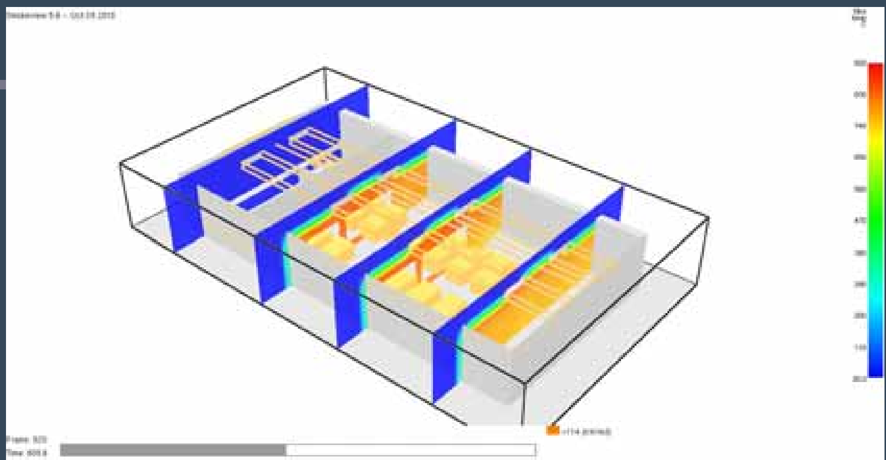
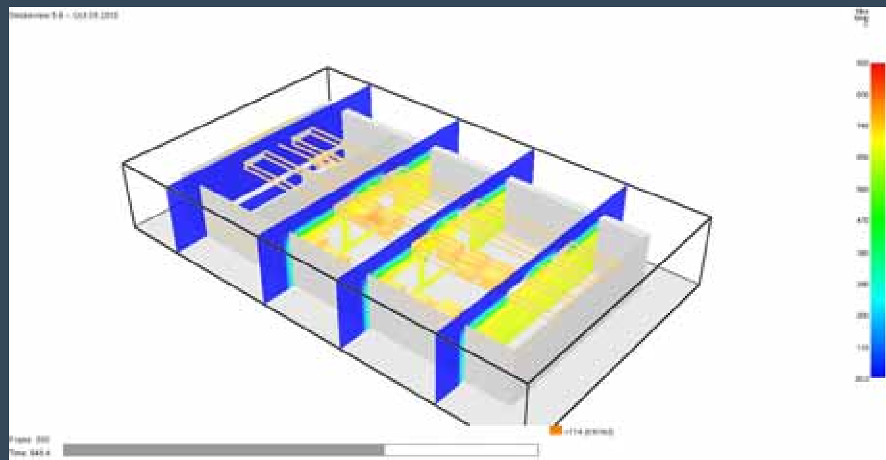
**Reference State:** All the windows are closed

**Scenario3:** 100% of the windows are broken

# W.P.4 Simulation of the natural fire event using CFD

## 1. Numerical simulation of the natural fire event in an industrial building using FDS

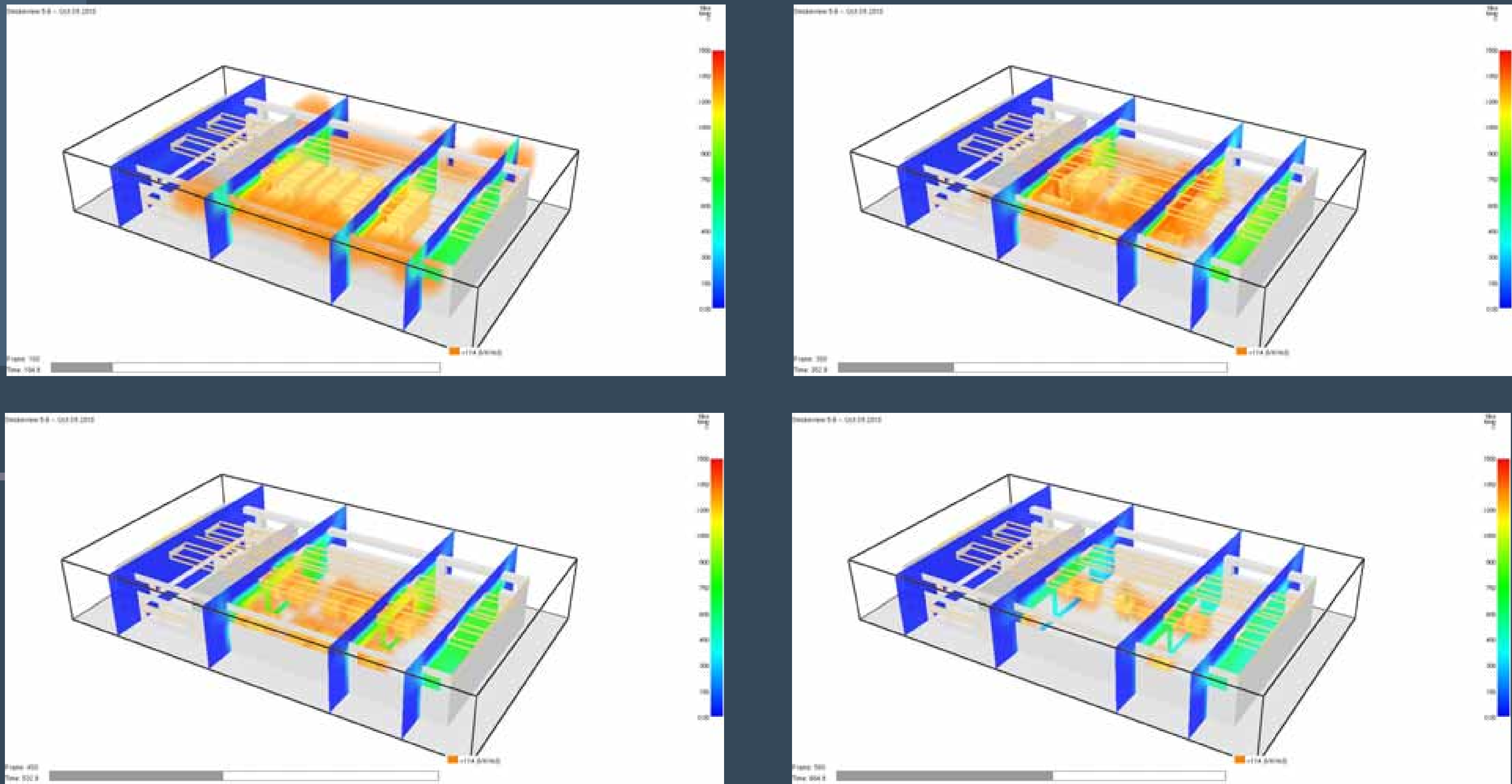
**Reference case:** All the windows are closed

## W.P.4 Simulation of the natural fire event using CFD

### 1. Numerical simulation of the natural fire event in an industrial building using FDS

**Scenario3:** 100% of the windows are open



## W.P.5 Numerical simulation of the structural behaviour of framed structures at elevated temperatures

✓The target of this W.P. is the development of FEA models using beam elements, for the simulation of the behaviour of frame structures at elevated temperatures

✓The numerical models are developed using the non-linear finite element code MSC Marc

✓The problem is handled through thermo-mechanical analysis

✓The objective is to obtain the fire resistance of model framed structures both using the ISO-fire curve and the temperature history results of the CFD analysis

✓Here the frame structures are assumed to have no fire protection

✓The validity of the numerical models, concerning the fire behaviour is obtained through the comparison with the FEA software Vulcan

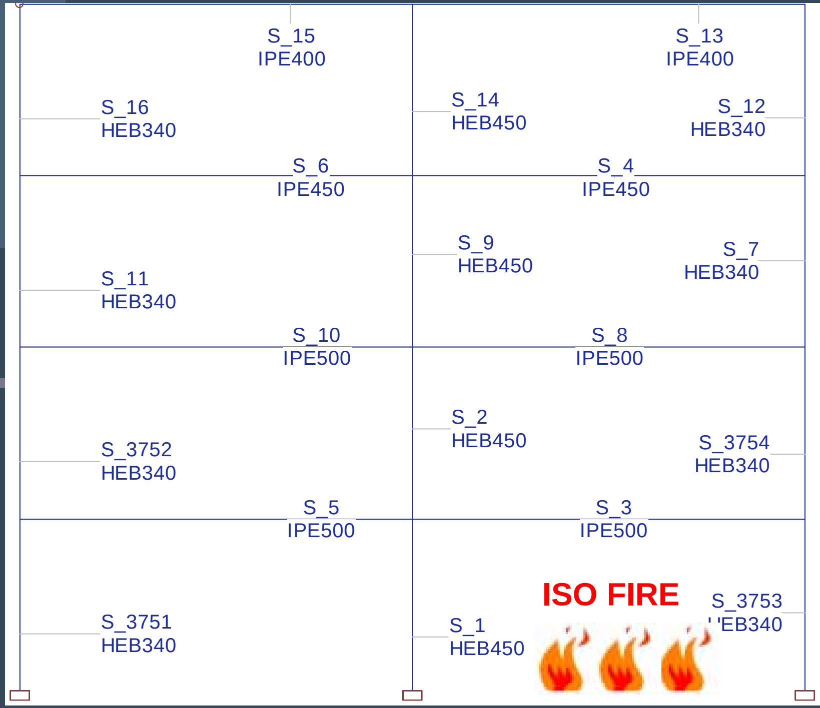
# W.P.5 Numerical simulation of the structural behaviour of framed structures at elevated temperatures

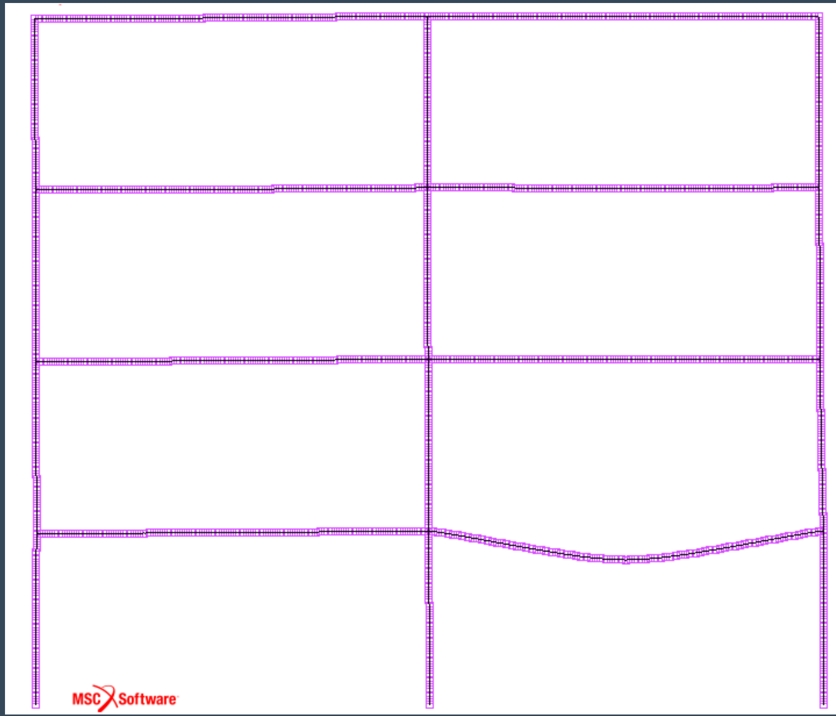
## 1. Numerical simulation of the fire behaviour of a 4th-storey steel frame

✓The numerical analysis indicates the fire resistance of the structure

✓The temperature of the structural members is calculated according to EC1

✓The geometrical non-linear 3D-analysis takes into account the material properties according to EC3




Fire resistance: 23 mins. Finally the system fails???????

# W.P.6 Analysis of framed structures under the combined scenario of fire after earthquake

✓ The objective of this W.P. is to obtain the behaviour of the model framed structures under the combined scenario of fire-after-earthquake

✓ This W.P. uses all the results of the previous W.P.

✓The non-linear analyses are conducted through the FEA code MSC Marc using 3D beam elements

Two different cases are considered

| Bare steel framed structures | Steel framed structures with fire protection |
|---|---|

A. <u>Bare steel framed structures</u>

✓ Analysis of the model structures for the combined scenario taking into account :
- o Different earthquake spectrums (W.P.3)
- o Different fire scenarios (W.P.4)

✓ Comparison of the fire resistance of the structure with the corresponding fire scenario of W.P.5

# W.P.6 Analysis of framed structures under the combined scenario of fire after earthquake

## B. Steel framed structures with fire protection

- ✓ Analysis of the structures for the combined scenario of fire-after-earthquake taking into account:
  - o the possible peeling of the fire-proof panting at the position of the plastic hinges due to earthquake
  - o different earthquake spectrums (W.P.3)
  - o different fire scenarios scenarios (W.P.4)
- ✓ Comparison of the fire resistance time of the structure with the reference case (according to the fire-proof painting)

**The final target is**

- ❖ to estimate the reduction of the fire resistance of the structure due to the combined scenario
- ❖ to relate this reduction to the level of the damage due to earthquake